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## Theoretical Modeling and Electromagnetic Response of Complex Metamaterials

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Program Manager: Dr. Arje Nachman

In this three year effort, we have made significant progress in understanding complex wave phenomena in artificial materials and metamaterials, and in proposing new exciting opportunities for technology offered by these artificial materials. Details about the various accomplishments can be found in the list of papers funded by this effort, and in the patents and patent applications protecting the new concepts developed during this work. The highlights of our work have been the introduction of the concept of magnet-free non-reciprocal devices based on angular-momentum bias, the concept of Floquet topological insulators for photons and phonons, new concepts based on parity-time symmetric metasurfaces, and various advances in electromagnetic and acoustic theory and applications. Our findings have opened various possibilities for technological breakthroughs, and some of our ideas, developed within this project, have been or are being experimentally verified by our group or other groups. Two of the inventions developed within this project, on which we have made significant progress in the past year, have been licensed to a startup company, Silicon Audio RF Circulator, which is working on the development and commercialization of magnetic-free circulators based on the concepts developed during this effort. We have been working to further improve the performance of these devices over several metrics, and we are excited by the prospect of replacing magnetic isolators and circulators with printed circuit implementations. Finally, we have continued our work on hyperbolic metasurfaces, which are opening interesting opportunities for nanophotonics. During this three-year period, we have published 80 journal papers supported by this project, including several in highly selective journals, and a few highlighted by the editors and breakthrough papers. We have also presented our research in a large number of plenary, keynote and invited talks, seminars and tutorials, and have filed 5 patents supported by this project. Overall, we have made significant progress on the exploration of the complex physics and wave interactions of metasurfaces and metamaterials, for applications of interest to the Department of Defense and the U.S. Air Force.

Relevant papers published during this effort, and supported by this project:

- J1. F. Monticone, and A. Alù, ***“Embedded Photonic Eigenvalues in 3D Nanostructures,”*** Physical Review Letters, Vol. 112, No. 21, 213903 (5 pages), May 29, 2014. [This paper has been selected as a PRL Editor’s Suggestion]
- J2. N. A. Estep, A. N. Askarpour, S. Trendafilov, G. Shvets, and A. Alù, ***“Transmission-Line Model and Propagation in a Negative-Index, Parallel-Plate Metamaterial to Boost Electron-Beam Interaction,”*** IEEE Transactions on Antennas and Propagation, Vol. 62, No. 6, pp. 3212-3221, June 1, 2014.
- J3. C. Argyropoulos, G. D’Aguanno, and A. Alù, ***“Giant Second Harmonic Generation Efficiency and Ideal Phase Matching with a Double Epsilon-Near-Zero Cross-Slit Metamaterial,”*** Physical Review B, Vol. 89, No. 23, 235401 (6 pages), June 3, 2014.
- J4. D. Sounas, and A. Alù, ***“Extinction Symmetry for Reciprocal Objects and Its Implications on Cloaking and Scattering Manipulation,”*** Optics Letters, Vol. 39, No. 13, pp. 4053-4056, June 27, 2014.

- J5. J. Lee, M. Tymchenko, C. Argyropoulos, P. Y. Chen, F. Lu, F. Demmerle, G. Boehm, M. C. Amann, A. Alù, and M. A. Belkin, ***“Giant Nonlinear Response from Plasmonic Metasurfaces Coupled to Intersubband Transitions,”*** *Nature*, Vol. 511, No. 7507, pp. 65-69, July 2, 2014. [This paper was highlighted on the general press, e.g., *Laser Physics World*, *Daily Texan*, UT Austin press release, Nanowerk]
- J6. R. Fleury, D. Sounas, and A. Alù, ***“Negative Refraction and Planar Focusing Based on Parity-Time Symmetric Metasurfaces,”*** *Physical Review Letters*, Vol. 113, No. 2, 023903 (5 pages), July 10, 2014.
- J7. R. Fleury, and A. Alù, ***“Manipulation of Electron Flow Using Near-Zero Index Semiconductor Metamaterials,”*** *Physical Review B*, Vol. 90, No. 3, 035138 (6 pages), July 29, 2014. [Fig. 5 from this paper has been selected for PRB Kaleidoscope]
- J8. J. C. Soric\*, R. Fleury\*, A. Monti, A. Toscano, F. Bilotti, and A. Alù, ***“Controlling Scattering and Absorption with Metamaterial Covers,”*** *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 8, pp. 4220-4229, August 1, 2014.
- J9. F. Monticone, and A. Alù, ***“Physical Bounds on Electromagnetic Invisibility and the Potential of Superconducting Cloaks,”*** *Photonics and Nanostructures - Fundamentals and Applications*, Special Issue for Metamaterials 2013, Vol. 12, No. 4, pp. 330-339, August 1, 2014, (*invited paper*).
- J10. P. Y. Chen, H. Huang, D. Akinwande, and A. Alù, ***“Graphene-Based Plasmonic Platform for Reconfigurable Terahertz Devices,”*** *ACS Photonics*, Vol. 1, No. 8, pp. 647-654, August 1, 2014.
- J11. A. N. Askarpour, Y. Zhao, and A. Alù, ***“Wave Propagation in Twisted Metamaterials,”*** *Physical Review B*, Vol. 90, 054305 (9 pages), August 25, 2014. [This paper was selected as Editor’s Suggestion]
- J12. P. Y. Chen, M. Farhat, A. N. Askarpour, M. Tymchenko, and A. Alù, ***“Infrared Beam-Steering Using Acoustically Modulated Surface Plasmons over a Graphene Monolayer,”*** *Journal of Optics*, Special Issue on Mid-IR and THz Photonics, Vol. 16, No. 9, 094008 (9 pages), September 3, 2014, (*invited paper*). [This paper has been selected as Journal of Optics’ Paper of the Week by the editors; This paper has been selected as a Journal of Optics Highlight of 2014]
- J13. Y. Wu, C. Zhang, N. Mohammadi Estakhri, Y. Zhao, J. Kim, M. Zhang, X. X. Liu, G. K. Pribi, A. Alù, C. K. Shih, and X. Li, ***“Intrinsic Optical Properties and Enhanced Plasmonic Response of Epitaxial Silver,”*** *Advanced Materials*, Vol. 26, No. 35, pp. 6106-6110, September 17, 2014, erratum at pp. 6054-6055, online at: <http://arxiv.org/abs/1306.5360>.
- J14. C. Argyropoulos, P. Y. Chen, G. D’Aguanno, and A. Alù, ***“Temporal Solitons in  $\epsilon$ -Near-Zero Plasmonic Channels,”*** *Optics Letters*, Vol. 39, No. 19, pp. 5566-5569, September 19, 2014.
- J15. J. Lee, S. Jung, P. Y. Chen, F. Lu, F. Demmerle, M. C. Amann, A. Alù, and M. A. Belkin, ***“Ultrafast Electrically-Tunable Polaritonic Metasurfaces,”*** *Advanced Optical Materials*, Vol. 2, No. 11, pp. 1057-1063, November 20, 2014. [This paper was featured on the inside front cover. This paper was selected for the Best of Advanced Optical Materials – 2014 edition]
- J16. N. Estep\*, D. Sounas\*, J. Soric, and A. Alù, ***“Magnetic-Free Non-Reciprocity Based on Parametrically Modulated Coupled-Resonator Loops,”*** *Nature Physics*, Vol. 10, No. 12, pp. 923-927, December 1, 2014. [This paper has been featured on a UT Austin press release, MIT Technology Review, Phys.org. A News and Views commentary by Ari Sihvola appeared in the same issue]
- J17. R. Fleury, and A. Alù, ***“Metamaterial Buffer for Broadband Non-Resonant Impedance Matching of Obliquely Incident Acoustic Waves,”*** *Journal of the Acoustical Society of America*, Vol. 136, No. 6, pp. 2935-2940, December 4, 2014.

- J18. R. Fleury, D. Sounas, and A. Alù, ***“An Invisible Acoustic Sensor Based on Parity-Time Symmetry,”*** Nature Communications, Vol. 6, No. 5905 (7 pages), January 6, 2015.
- J19. N. Mohammadi Estakhri, and A. Alù, ***“Ultra-Thin Unidirectional Carpet Cloak and Wavefront Reconstruction with Graded Metasurfaces,”*** IEEE Antennas and Wireless Propagation Letters, Special Cluster on Transformation Electromagnetics, Vol. 13, pp. 1775-1778, January 28, 2015, *(invited paper)*.
- J20. N. Estep, A. N. Askarpour, and A. Alù, ***“Experimental Demonstration of Negative-Index Propagation in a Rectangular Waveguide Loaded with Complementary Split-Ring Resonators,”*** IEEE Antennas and Wireless Propagation Letters, Vol. 14, pp. 119-122, February 2, 2015.
- J21. S. Savoia, G. Castaldi, V. Galdi, A. Alù, and N. Engheta, ***“PT -Symmetry-Induced Wave Confinement and Guiding in Epsilon-Near-Zero Metamaterials,”*** Physical Review B, Vol. 91, No. 11, 115114 (10 pages), March 5, 2015, online at: <http://arxiv.org/abs/1502.05495>.
- J22. X. Ding, F. Monticone, K. Zhang, L. Zhang, D. Gao, S. N. Burokur, A. de Lustrac, Q. Wu, C. W. Qiu, and A. Alù, ***“Ultrathin Pancharatnam-Berry Metasurface with Maximal Cross-Polarization Efficiency,”*** Advanced Materials, Vol. 27, No. 7, pp. 1195-1200, February 18, 2015.
- J23. A. Monti, J. Soric, A. Alù, A. Toscano, and F. Bilotti, ***“Anisotropic Mantle Cloaks for TM and TE Scattering Reduction,”*** IEEE Transactions on Antennas and Propagation, Vol. 63, No. 4, pp. 1775-1788, April 1, 2015.
- J24. F. Monticone, and A. Alù, ***“Leaky-Wave Theory, Techniques and Applications: From Microwaves to Visible Frequencies,”*** Proceedings of IEEE, Vol. 103, No. 5, pp. 793-821, May 26, 2015, *(invited paper)*.
- J25. R. Fleury, D.L. Sounas, and A. Alù, ***“Subwavelength Ultrasonic Circulator Based on Spatio-Temporal Modulation,”*** Physical Review B, Vol. 91, No. 17, 174306 (9 pages), May 28, 2015.
- J26. B. Orazbayev, N. Mohammadi Estakhri, M. Beruete, and A. Alù, ***“Terahertz Carpet Cloak Based on a Ring Resonator Metasurface,”*** Physical Review B, Vol. 91, No. 19, 195444 (5 pages), May 29, 2015.
- J27. B. Hopkins, D. S. Filonov, A. E. Miroshnichenko, F. Monticone, A. Alù, and Y. S. Kivshar, ***“Interplay of Magnetic Responses in All-Dielectric Oligomers to Realize Magnetic Fano Resonances,”*** ACS Photonics, Vol. 2, No. 6, pp. 724-729, June 1, 2015.
- J28. J. S. Gomez-Diaz, M. Tymchenko, and A. Alù, ***“Hyperbolic Plasmons and Topological Transitions over Uniaxial Metasurfaces,”*** Physical Review Letters, Vol. 114, No. 23, 233901 (5 pages), June 11, 2015.
- J29. J. C. Soric, A. Monti, A. Toscano, F. Bilotti, and A. Alù, ***“Multiband and Wideband Bilayer Mantle Cloaks,”*** IEEE Transactions on Antennas and Propagation, Vol. 63, No. 7, pp. 3235-3240, July 2015.
- J30. D. L. Sounas, R. Fleury, and A. Alù, ***“Unidirectional Cloaking Based on Metasurfaces with Balanced Loss and Gain,”*** Physical Review Applied, Vol. 4, 014005 (11 pages), July 16, 2015.
- J31. N. Mohammadi Estakhri, C. Argyropoulos, and A. Alù, ***“Graded Metascreens to Enable a New Degree of Nanoscale Light Management,”*** Philosophical Transactions A, Special Issue on Spatial Transformations: from Fundamentals to Applications, Vol. 373, No. 2049, 20140351 (15 pages), July 27, 2015, *(invited paper)*.
- J32. C. Valagiannopoulos, and A. Alù, ***“The Role of Reactive Energy in the Flow of Energy Radiated by a Dipole Antenna,”*** IEEE Transactions on Antennas and Propagation, Vol. 63, No. 8, pp. 3736-3741, August 2, 2015.
- J33. P. Y. Chen, C. Argyropoulos, G. D’Aguanno, and A. Alù, ***“Enhanced Second-Harmonic Generation by Metasurface Nanomixer and Nanocavity,”*** ACS Photonics, Vol. 2, No. 8, pp. 1000-1006, August 27, 2015.

- J34. R. Fleury\*, F. Monticone\*, and A. Alù, ***“Invisibility and Cloaking: Origins, Present, and Future Perspectives,”*** Physical Review Applied, Vol. 4, No. 3, 037001 (20 pages), September 1, 2015, (*invited review paper*).
- J35. R. Fleury, D. L. Sounas, M. R. Haberman, and A. Alù, ***“Nonreciprocal Acoustics,”*** Acoustics Today, Vol. 11, No. 3, pp. 14-21, September 1, 2015, (*invited review paper*).
- J36. Y. Hadad, D. L. Sounas, and A. Alù, ***“Space-Time Gradient Metasurfaces,”*** Physical Review B, Rapid Communications, Vol. 92, No. 10, 100304R (6 pages), September 22, 2015, online at: <http://arxiv.org/abs/1506.00690>.
- J37. J. S. Gomez-Diaz, M. Tymchenko, and A. Alù, ***“Hyperbolic Metasurfaces: Surface Plasmons, Light-Matter Interactions, and Physical Implementation using Graphene Strips,”*** Optical Materials Express, Special Feature Issue on Plasmonics, Vol. 5, Issue 10, pp. 2313-2329, September 24, 2015, (*invited paper*).
- J38. A. B. Khanikaev\*, R. Fleury\*, H. Mousavi, and A. Alù, ***“Topologically Robust Sound Propagation in an Angular-Momentum-Biased Graphene-Like Resonator Lattice,”*** Nature Communications, Vol. 6, No. 8260 (7 pages), October 7, 2015.
- J39. J. C. Soric, A. Monti, A. Toscano, F. Bilotti, and A. Alù, ***“Dual-Polarized Reduction of Dipole Antenna Blockage Using Metasurface Cloaks,”*** IEEE Transactions on Antennas and Propagation, Vol. 63, No. 11, pp. 4027-4034, November 2015.
- J40. D. Correias-Serrano, J. S. Gomez-Diaz, M. Tymchenko, and A. Alù, ***“Nonlocal Response of Hyperbolic Metasurfaces,”*** Optics Express, Special Feature Issue on Surface Plasmon Photonics, Vol. 23, No. 23, pp. 29434-29448, November 4, 2015, (*invited paper*).
- J41. J. C. Soric, and A. Alù, ***“Longitudinally Independent Matching and Arbitrary Wave Patterning Using  $\epsilon$ -Near-Zero Channels,”*** IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No. 11, pp. 3558-3567, November 2015.
- J42. D. Ramaccia, D. L. Sounas, A. Alù, F. Bilotti, A. Toscano, ***“Non-Reciprocal Horn Antennas Using Angular Momentum-Biased Metamaterial Inclusions,”*** IEEE Transactions on Antennas and Propagation, Vol. 63, No. 12, pp. 5593-5600, December 2015.
- J43. C. A. Valagiannopoulos, A. N. Askarpour, and A. Alù, ***“Aharonov-Bohm Detection of Two-Dimensional Magnetostatic Cloaks,”*** Physical Review B, Vol. 92, No. 22, 224414 (6 pages), December 10, 2015.
- J44. N. Mohammadi Estakhri, and A. Alù, ***“Recent Progress in Gradient Metasurfaces,”*** Journal of the Optical Society of America B, Special Feature Issue on Electromagnetic Metasurfaces, Vol. 33, No. 2, pp. A21-A30, December 16, 2015, (*invited paper*).
- J45. P. Y. Chen, K. Q. Le, and A. Alù, ***“Nonlinear Nanocircuitry Based on Quantum Tunneling Effects,”*** MRS Communications, Vol. 5, No. 4, pp. 565-571, December 24, 2015, (*invited paper*).
- J46. F. Qin, L. Ding, L. Zhang, F. Monticone, C. C. Chum, J. Deng, S. Mei, Y. Li, J. Teng, M. Hong, S. Zhang, A. Alù, and C. W. Qiu, ***“Hybrid Bilayer Plasmonic Metasurface Efficiently Manipulates Visible Light,”*** Science Advances, Vol. 2, No. 1, e1501168 (8 pages), January 1, 2016. [This paper was highlighted in Nature Physics 12, 111 (2016)]
- J47. N. A. Estep, D. L. Sounas, and A. Alù, ***“Magnetless Microwave Circulators Based on Spatiotemporally Modulated Rings of Coupled Resonators,”*** IEEE Transactions on Microwave Theory and Techniques, Vol. 64, No. 2, pp. 502-518, February 1, 2016.
- J48. M. Moccia, G. Castaldi, V. Galdi, A. Alù, and N. Engheta, ***“Dispersion Engineering Via Nonlocal Transformation Optics,”*** Optica, Vol. 3, No. 2, pp. 179-188, February 10, 2016.
- J49. S. Cummer, J. Christensen, and A. Alù, ***“Controlling Sound with Acoustic Metamaterials,”*** Nature Reviews Materials, Vol. 1, No. 16001, February 16, 2016, (*invited paper*).



- J50. A. Monti,\* J. Soric,\* M. Barbuto, D. Ramaccia, S. Vellucci, F. Trotta, A. Alù, A. Toscano, and F. Bilotti, **"Mantle Cloaking for Co-Site Radio-Frequency Antennas,"** Applied Physics Letters, Vol. 108, 113502 (5 pages), March 15, 2016.
- J51. C. Valagiannopoulos,\* F. Monticone,\* and A. Alù, **"PT-Symmetric Planar Devices for Field Transformation and Imaging,"** Journal of Optics, Special Issue on Transformation Optics, Vol. 18, No. 4, 044028 (11pages), April 1, 2016, (*invited paper*).
- J52. Y. Hadad, A. B. Khanikaev, and A. Alù, **"Self-Induced Topological Transitions and Edge States Supported by Nonlinear Staggered Potentials,"** Physical Review B, Vol. 93, No. 15, 155112 (8 pages), April 7, 2016, online at: <http://arxiv.org/abs/1512.05763>.
- J53. Y. Hui, J. S. Gomez-Diaz, Z. Qian, A. Alù, and M. Rinaldi, **"Plasmonic Piezoelectric Nanomechanical Resonator for Spectrally Selective Infrared Sensing,"** Nature Communications, Vol. 7, No. 11249 (9 pages), April 15, 2016.
- J54. D. L. Sounas, and A. Alù, **"Color Separation through Spectrally-Selective Optical Funneling,"** ACS Photonics, Vol. 3, pp. 620-626, May 1, 2016.
- J55. R. Maas, S. A. Mann, D. L. Sounas, A. Alù, E. C. Garnett, and A. Polman, **"Generalized Anti-Reflection Coatings for Complex Bulk Metamaterials,"** Physical Review B, Vol. 93, No. 19, 195433 (7 pages), May 24, 2016.
- J56. M. A. Miri, and A. Alù, **"Nonlinearity-Induced PT-Symmetry Without Material Gain,"** New Journal of Physics, Focus Issue on Parity-Time Symmetry in Optics and Photonics, Vol. 18, 065001 (8 pages), May 31, 2016, (*invited paper*), online at: <https://arxiv.org/abs/1605.06151>.
- J57. L. Langguth, R. Fleury, A. Alù, and A. F. Koenderink. **"The Drexhage Experiment for Sound,"** Physical Review Letters, Vol. 116, No. 22, 224301 (6 pages), June 1., 2016. [This paper has been selected as Editor's Suggestion and highlighted with a Synopsis in Physics]
- J58. X. X. Liu, Y. Zhao, and A. Alù, **"Polarizability Tensor Retrieval for Subwavelength Particles of Arbitrary Shape,"** IEEE Transactions on Antennas and Propagation, Vol. 64, No. 6, pp. 2301-2310, June 1, 2016.
- J59. D. Correas-Serrano, J. S. Gomez-Diaz, D. L. Sounas, Y. Hadad, A. Alvarez-Melcon, and A. Alù, **"Nonreciprocal Graphene Devices and Antennas Based on Spatiotemporal Modulation,"** IEEE Antennas and Wireless Propagation Letters, Special Cluster on Graphene and Two-Dimensional Materials for Antenna Applications, Vol. 15, pp. 1529-1532, June 2, 2016, (*invited paper*).
- J60. R. Fleury, D. L. Sounas, and A. Alù, **"Parity-Time Symmetry in Acoustics: Theory, Devices, and Potential Applications,"** IEEE Journal of Selected Topics in Quantum Electronics, Vol. 22, No. 5, 5000809 (9 pages), June 13, 2016, (*invited paper*).
- J61. Y. Ràdi, D. L. Sounas, A. Alù, and S. A. Tretyakov, **"Parity-Time Symmetric Tunneling: Nearly Ideal Angular and Frequency Filter,"** Physical Review B, Vol. 93, No. 23, 235427 (7 pages), June 15, 2016.
- J62. R. Fleury\*, A. Khanikaev\*, and A. Alù, **"Floquet Topological Insulators for Sound,"** Nature Communications, Vol. 7, No. 11744 (11 pages), June 17, 2016, online at <http://arxiv.org/abs/1511.08427>.
- J63. F. Monticone, and A. Alù, **"Invisibility Exposed: Physical Bounds on Passive Cloaking,"** Optica, Vol. 3, No. 7, pp. 718-724, July 5, 2016. [This work was covered by a UT Austin press release]
- J64. A. Alù, **"Engineering Mid-Infrared and Optical Nonlinearities with Metamaterials,"** Journal of Optics, in A. M. Urbas, Z. Jacob, L. Dal Negro, N. Engheta, A. D. Boardman, P. Egan, A. B. Khanikaev, V. Menon, M. Ferrera, N. Kinsey, C. De Vault, J. Kim, V. Shalae, A. Boltasseva, J. Valentine, C. Pfeiffer, A. Grbic, E. Narimanov, L. Zhu, S. Fan, A. Alù, E. Poutrina, N. M. Litchinitser, M. A. Noginov, K. F. MacDonald, E. Plum, X. Liu, P. F. Nealey, C. R. Kagan, C. B. Murray, D. A. Pawlak, I. I. Smolyaninov, V. N. Smolyaninova, and D. Chanda, Topical Review, "Roadmap on Optical Metamaterials," Vol. 18, 093005 (53 pages), August 9, 2016, (*invited paper*).



- J65. M. Farhat, P. Y. Chen, S. Guenneau, H. Bagci, K. N. Salama, and A. Alù, ***“Cloaking Through Cancellation of Diffusive Wave Scattering,”*** Proceedings of the Royal Society A, Vol. 472, 20160276 (11 pages), August 10, 2016, online at: <http://arxiv.org/pdf/1603.00985.pdf>.
- J66. D. Correias-Serrano, J. S. Gomez-Diaz, A. Alvarez Melcon, and A. Alù, ***“Black Phosphorus Plasmonics: Anisotropic Elliptical Propagation and Nonlocality-Induced Canalization,”*** Journal of Optics, Special Issue on Quantum Plasmonics, Vol. 18, No. 10, 104006 (10 pages), September 22, 2016, (*invited paper*), online at: <http://arxiv.org/abs/1608.01617>.
- J67. J. Kim, S. Choudhury, C. DeVault, Y. Zhao, A. V. Kildishev, V. M. Shalaez, A. Alù, and A. Boltasseva, ***“Controlling the Polarization State of Light with Plasmonic Metal Oxide Metasurface,”*** ACS Nano, Vol. 10, No. 10, pp. 9326-9333, October 5, 2016.
- J68. N. Mohammadi Estakhri, and A. Alù, ***“Wavefront Transformation with Gradient Metasurfaces,”*** Physical Review X, Vol. 6, No. 4, 041008 (17 pages), October 14, 2016.
- J69. F. Monticone,\* C. A. Valagiannopoulos,\* and Andrea Alù, ***“Aberration-Free Imaging Based on Parity-Time Symmetric Nonlocal Metasurfaces,”*** Physical Review X, Vol. 6, 041018 (13 pages), October 25, 2016, online at: <http://arxiv.org/abs/1509.07300>.
- J70. D. G. Baranov, S. V. Makarov, A. E. Krasnok, P. A. Belov, and A. Alù, ***“Tuning of Near- and Far-Field Properties of All-dielectric Dimer Nanoantennas via Ultrafast Electron-Hole Plasma Photoexcitation,”*** Laser and Photonics Reviews, Vol. 10, No. 6, pp. 1009-1015, November 11, 2016, online at: <http://arxiv.org/abs/1606.05199>.
- J71. B. Orazbayev, N. Mohammadi Estakhri, A. Alù, and M. Beruete, ***“Experimental Demonstration of Metasurface-Based Ultrathin Carpet Cloak for Millimetre Waves,”*** Advanced Optical Materials, Vol. 5, No. 1, 1600606 (5 pages), November 15, 2016.
- J72. J. S. Gomez-Diaz, and A. Alù, ***“Flatland Optics with Hyperbolic Metasurfaces,”*** ACS Photonics, Vol. 3, No. 12, pp 2211–2224, November 16, 2016, (*invited paper*).
- J73. A. Monti, J. Soric, A. Alù, A. Toscano, and F. Bilotti, ***“Design of Cloaked Yagi-Uda Antennas,”*** EPJ Applied Metamaterials, Vol. 3, No. 10 (7 pages), November 23, 2016.
- J74. M. Tymchenko, J. S. Gomez-Diaz, J. Lee, N. Nookala, M. Belkin, and A. Alù, ***“Advanced Control of Nonlinear Beams with Pancharatnam-Berry Metasurfaces,”*** Physical Review B, Vol. 94, 214303 (13 pages), December 14, 2016. [This paper has been selected for PRB Kaleidoscope]
- J75. Y. Zhao, A. N. Askarpour, L. Sun, J. Shi, X. Li, and A. Alù, ***“Chirality Detection of Single-Enantiomer Drugs Using Twisted Optical Metamaterials,”*** Nature Communications, No. 14180 (8 pages), January 25, 2017.
- J76. F. Monticone, and A. Alù, ***“Metamaterial, Plasmonic and Nanophotonic Devices,”*** Reports on Progress in Physics, Vol. 80, No. 3, 036401 (37 pages), February 6, 2017, (*invited paper*).
- J77. D. Ramaccia, D. L. Sounas, A. Alù, A. Toscano, F. Bilotti, ***“Doppler Cloak Restores Invisibility to Objects in Relativistic Motion,”*** Physical Review B, Vol. 95, 075113 (6 pages), February 6, 2017.
- J78. A. H. Schokker, F. van Riggelen, Y. Hadad, A. Alù, and A. F. Koenderink, ***“Systematic Study of the Hybrid Plasmonic-Photonic Band Structure Underlying Lasing Action of Diffractive Plasmon Particle Lattices,”*** Physical Review B, Vol. 95, 085409 (14 pages), February 8, 2017.
- J79. C. Coullais, D. L. Sounas, and A. Alù, ***“Static Non-Reciprocity Using Mechanical Metamaterials,”*** Nature, Vol. 542, No. 7642, pp. 461-464, February 13, 2017.
- J80. N. Mohammadi Estakhri\*, V. Neder\*, M. W. Knight, A. Polman, and A. Alù, ***“Visible Light, Wide-Angle Graded Metasurface for Back Reflection,”*** ACS Photonics, Vol. 4, No. 2, pp. 228-235, February 23, 2017.

Relevant patent applications filed during this effort, and supported by this project:

- P1. Patent Application, with title '**Eliminating Reciprocity Constraints in Radiating and Scattering Systems with Spatio-Temporal Modulation**,' joint inventors: Yakir Hadad, Jason Soric, Andrea Alù, assignee: The University of Texas at Austin, February 26, 2015.
- P2. Patent Application, with title '**Magnetless Non-Reciprocal Devices Using Modulated Filters**,' joint inventors: Ahmed Kord, Dimitrios Sounas, Andrea Alù, assignee: The University of Texas at Austin, September 16, 2016.
- P3. Patent Application No. 62/066,570, with title '**Methods for Sample Characterization**,' joint inventors: Yang Zhao, Andrea Alù, assignee: The University of Texas at Austin, October 21, 2014.
- P4. Patent Application No. US2015/032875, with title '**Parity-Time Symmetric Metasurfaces and Metamaterials**,' joint inventors: Romain Fleury, Dimitrios Sounas, Andrea Alù, assignee: The University of Texas at Austin, May 28, 2015.

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The University of Texas at Austin

## Grant/Contract Title

The full title of the funded effort.

Theoretical Modeling and Electromagnetic Response of Complex Metamaterials

## Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0204

## Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Andrea Alu

## Program Officer

The AFOSR Program Officer currently assigned to the award

Dr. Arje Nachman

## Reporting Period Start Date

09/30/2013

## Reporting Period End Date

11/30/2016

## Abstract

In this three year effort, we have made significant progress in understanding complex wave phenomena in artificial materials and metamaterials, and in proposing new exciting opportunities for technology offered by these artificial materials. Details about the various accomplishments can be found in the list of papers funded by this effort, and in the patents and patent applications protecting the new concepts developed during this work. The highlights of our work have been the introduction of the concept of magnet-free non-reciprocal devices based on angular-momentum bias, the concept of Floquet topological insulators for photons and phonons, new concepts based on parity-time symmetric metasurfaces, and various advances in electromagnetic and acoustic theory and applications. Our findings have opened various possibilities for technological breakthroughs, and some of our ideas, developed within this project, have been or are being experimentally verified by our group or other groups. Two of the inventions developed within this project, on which we have made significant progress in the

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past year, have been licensed to a startup company, Silicon Audio RF Circulator, which is working on the development and commercialization of magnetic-free circulators based on the concepts developed during this effort. We have been working to further improve the performance of these devices over several metrics, and we are excited by the prospect of replacing magnetic isolators and circulators with printed circuit implementations. Finally, we have continued our work on hyperbolic metasurfaces, which are opening interesting opportunities for nanophotonics. During this three-year period, we have published 80 journal papers supported by this project, including several in highly selective journals, and a few highlighted by the editors and breakthrough papers. We have also presented our research in a large number of plenary, keynote and invited talks, seminars and tutorials, and have filed 5 patents supported by this project. Overall, we have made significant progress on the exploration of the complex physics and wave interactions of metasurfaces and metamaterials, for applications of interest to the Department of Defense and the U.S. Air Force.

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P1. Patent Application, with title 'Eliminating Reciprocity Constraints in Radiating and Scattering Systems with Spatio-Temporal Modulation', joint inventors: Yakir Hadad, Jason Soric, Andrea Alù, assignee: The University of Texas at Austin, February 26, 2015.

P2. Patent Application, with title 'Magnetless Non-Reciprocal Devices Using Modulated Filters', joint inventors: Ahmed Kord, Dimitrios Sounas, Andrea Alù, assignee: The University of Texas at Austin, September 16, 2016.

P3. Patent Application No. 62/066,570, with title 'Methods for Sample Characterization', joint inventors: Yang Zhao, Andrea Alù, assignee: The University of Texas at Austin, October 21, 2014.

P4. Patent Application No. US2015/032875, with title 'Parity-Time Symmetric Metasurfaces and Metamaterials', joint inventors: Romain Fleury, Dimitrios Sounas, Andrea Alù, assignee: The University of Texas at Austin, May 28, 2015.

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Supplies			
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